CALIFORNIA DIVISION OF MINES AND GEOLOGY

FAULT EVALUATION REPORT FER-238

CALICO FAULT AND ADJACENT 1992 SURFACE RUPTURES NEAR NEWBERRY SPRINGS, SAN BERNARDINO COUNTY

by

Earl W. Hart
Geologist
August 26, 1994

INTRODUCTION

On June 28, 1992, ground ruptures occurred along a previously unrecognized fault zone north and east of Newberry Springs in association with the M7.3 Landers earthquake. These ruptures, which appear to be a northern branch of the Calico fault, lie outside the existing Earthquake Fault Zones[1] established for the Calico Fault in 1988 in the Harvard Hill, Newberry Springs, and Troy Lake 7.5-minute quadrangles (CDMG, 1988) (see Figure 4 for location). Because these ruptures appear to be faults and to meet the zoning criteria of "sufficiently active and well-defined" (Hart, 1994), they will be evaluated here for zoning under the Alquist-Priolo Earthquake Fault Zoning Act. A secondary purpose of this report is to re-evaluate the adjacent Calico Fault. Figures 1 and 4 identify the study area, 1992 rupture area, and associated faults.

The Calico Fault is an important element of a broad zone of northwest-trending faults within the central and eastern parts of the Mojave block. According to Dokka and Travis (1990a, 1990b), these faults, along with faults of the Death Valley region to the north, comprise the Eastern California Shear Zone (ECSZ) along which 65 km of right-lateral shear has occurred in the last 6-10 m.y. This equates to a slip rate of 6-12 mm/yr. They believe that, although most of this shear has occurred in the eastern part of the Mojave Desert block, the locus of tectonism has shifted westward to the south-central part of the block in the last 0.7 to 1.5 Ma. Sauber and others (1994) determined a right-lateral strain across the central Mojave Desert block (from the

---

[1] The designations "Special Studies Zones" and Alquist-Priolo Special Studies Zones Act were changed to "Earthquake Fault Zones" and Alquist-Priolo Earthquake Fault Zoning Act, respectively, on January 1, 1994.

Helendale Fault to the Ludlow Fault; see Figure 1) of about 12 mm/yr based on geodetic measurements.

Quaternary faults in the south-central Mojave Desert (Figure 1) have been mapped and evaluated by Bull (1978), Morton and others (1980), and Hart and others (1988). Classifications by age, based on the existing literature at the time, were made by Bortugno and Spittler (1986) and Jennings (1992).

The principal faults of the central Mojave were evaluated by CDMG in 1986 and 1987 as part of a statewide program. Those faults considered to be Holocene-active and well-defined as surface features were subsequently zoned. This work is detailed in unpublished Fault Evaluation Reports (FERs) and the results are summarized by Hart and others (1988). At that time, little attention was paid to minor faults in this relatively undeveloped region and very little effort was made to search for north- or northeast-trending faults. An evaluation of the Calico Fault was previously made by Bortugno (1987).

SUMMARY OF AVAILABLE DATA

The M7.3 Landers earthquake of June 28, 1992 occurred along a north-trending rupture zone involving segments of several faults in the central Mojave Desert (Figure 1). Rupture was initiated on the southern end of the Johnson Valley Fault and propagated northward along the Kickapoo, Homestead Valley, Emerson and Camp Rock Faults. Surface rupture also extended southward along the Burnt Mountain and Eureka Peak Faults, totalling 85 km of overall length (Hart and others, 1993; Sieh and others, 1993).

Fault rupture was triggered on perhaps a dozen other faults -- some not named or previously mapped (Hart and others, 1993). One of these previously unmapped faults lies just east of Newberry Springs and appears to be a northerly splay of the Calico fault. This splay is referred to as the Newberry Fracture Zone by Unruh and others (1994) and is the primary subject of this study. For completeness, the adjacent segment of the Calico Fault also is re-evaluated in the Harvard Hill, Newberry Springs, and Troy Lake quadrangles (Figures 2a and 2b).

Newberry Fracture Zone

Ruptures in this fracture zone were first reported shortly after the Landers earthquake of June 28, 1992 by Al Barrows and Steve Bezore of CDMG (Field notes of Barrows, 7/7/92). They noted several sets of northeast-trending cracks between Valley Center and Silver Valley Roads and measured a maximum of 6 cm of vertical offset. Their locations, shown on Figure 2a, are

considered to be approximate as they did not have large scale air photos and plotted their observations directly on USGS topographic maps. Prior to the discovery of these fractures, there was no evidence in the geologic literature that a fault existed in this area (Dibblee and Bassett, 1966; Morton and others, 1980; Bortugno, 1987).

More complete mapping of the Newberry Fracture Zone was done by William Lettis and Associates (WLA) from September 29 to October 6, 1992 using large-scale, low-sun-angle aerial photos of I.K. Curtis (flown August 24, 1992) and field mapping. The southernmost segment of the fracture zone, however, lacks aerial photo coverage and was surveyed using a brunton compass and tape measure (Figure 3). They identified most of the significant cracks and walked-out and measured many of those (J.M. Sowers, personal communication, 1992, 1993). The mapped traces of WLA were later slightly modified and published by Unruh and others (1994) (see Figures 2a and 2b). The results were initially summarized in an abstract by Lettis and Kelson (1992).

According to Unruh and others (1994), the fracture zone is comprised of a series of left-stepping, north- to northeast-trending fractures that could be traced for about 10 km (6 mi.) (Figures 2a and 2b). The fractures had a normal dip-slip separation to 12 cm and apparent "lateral" (extensional?) offsets to 5 cm. The sense of slip measured, based on displaced features along the fractures, show the mean slip direction to be nearly perpendicular to the fracture trend (i.e., northwest-southeast extension). They reported that the "fractures border the margins of several preexisting en echelon elongate depressions 1 to 2 m deep, suggesting that similar deformations have occurred repeatedly in the past". The relationship of these fractures to preexisting scarps, based on this writer's (Hart) photo interpretation of the 1952-53 U.S. Department of Agriculture aerial photos, is shown on Figure 2a and 2b.

In order to expedite this writer's interpretation of the I.K. Curtis airphotos, photocopies of WLA's photo overlays were obtained from WLA through the courtesy of J.M. Sowers, who participated in the post-earthquake investigation for WLA. The photo overlays contained useful field measurements, which are partly plotted on Figure 3. Other field data also were kindly provided. I carefully reinterpreted the I.K. Curtis photos, adding and extending a number of fracture traces to WLA's photo overlays and verifying other traces. It was not until March 1994, however, that I was able to field check some of the fractures, many of which were still preserved, albeit in a somewhat degraded condition. But even at that late date, vertical offsets on scarplets could still be measured with some confidence. My field observations are noted on Figure 3.

K.R. Lajoie (1994) also provided a detailed photointerpretation on the locations of fractures. His mapping was plotted on overlays to photo-mozaics of flight lines of the 1:4,000-scale I.K. Curtis airphotos. Many of his mapped fractures were field-checked and verified by him in November 1993. However, other traces could not be verified at this late date. I also photo-checked his work and could verify the large majority of his traces, but not all. An annotated copy of his mapping is included at the original scale in Appendix A of this report. Because of the detail in his mapping, no attempt was made to transfer all of his traces to the 1:24,000 scale topo map. Instead, his generalized mapping was used to modify the work of WLA and this writer. His detailed map provides useful insight as to the detail and complexity of faulting that occurred. His work also may be useful in locating individual fracture traces with respect to the siting of future structures, particularly when used in conjunction with the I.K. Curtis airphotos.

The fracture traces shown on Figure 3 are a compilation of fractures mapped by WLA (Unruh and others, 1994), K.R. Lajoie and myself. Because of the reduction in scale between the airphotos and base map, the traces have been somewhat generalized. In addition, there were relatively few reference points on the air photos that could be accurately located on the topographic maps. Because of these factors the transfer of data was as follows: 1) The combined traces plotted on the photo overlays were transferred to 1:24,000-scale orthophoto maps of the Newberry Springs area visually (i.e., "eye-balled") and b) The traces were then traced onto topographic maps. The user of these maps is cautioned that some of the traces may be slightly mislocated and that the portrayal of data is somewhat generalized. Therefore, reference should be made to the I.K. Curtis photos for the most accurate location of the cracks. The overlays of Lajoie (Appendix A) should facilitate the identification process.

Figure 3 shows that the 1992 fractures form several sets of left-stepping normal faults, some of which also define left-stepping grabens. The maximum vertical displacement reported (WLA notes) is 11 cm with up to 5 cm of horizontal separation (mostly pure extension). A left-lateral component of slip was reported at only one location (north of Valley Center Road by WLA), although right- or left-lateral components would have been difficult to measure in the soft sandy soils. Many of the larger cracks (Figure 3) coincided with preexisting scarps and associated tonal lineaments shown on Figures 2a and 2b. The surface on which these features are developed is underlain by late Pleistocene flood plain deposits of the Mojave River veneered by thin deposits of Holocene windblown sand and alluvium (Dibblee and Bassett, 1966; John Tinsley, p.c., 1994). On the ground some of the grabens are estimated to be as much as 2 m

deep, suggesting repeated extensional ground rupture during latest Quaternary time.

If the Landers event is assumed to be characteristic of the magnitude of vertical deformation, then 10 to 20 rupture events of 10 cm each would have occurred since the surface was formed. If the surface is 10,000 years old, then this would mean one event every 500-1000 years. If the surface is older, then the recurrence between events would be less frequent.

It should be noted that the 1992 fracture traces in section 35 just north of Highway I-40 appear to lie about 50 m (150 ft) or so west of the principal zone of weak tonal lineaments shown on Figure 2a. Although the tonal features and associated scarps may not be the same faults that ruptured in 1992 or perhaps may not represent previous fractures at all, it is possible that there is a relationship with some of the features shown and that the 1992 fractures may not have been located accurately by the brunton and tape survey of WLA. The purpose of this caveat is to remind the users of these maps that some of the fracture traces may not be located accurately and need to be verified for building setback/avoidance purposes.

Calico Fault

The Calico Fault was previously evaluated and recommended for zoning under the Alquist-Priolo Act by E.J. Bortugno (1987). The fault is part of a 90 km (60 mi) long right-lateral fault zone that also includes the West Calico and Hidalgo Faults to the southeast (Figure 1). Based mainly on the work of Bull (1978), Morton and others (1985), and his own investigation for CDMG, Bortugno concluded that the fault was Holocene active and well-defined based on geomorphic expression and offsets of latest Quaternary deposits. The fault traces used for zoning and the Earthquake Fault Zones boundaries delineated within the study area are shown on Figures 2a and 2b. The fault traces shown are based on Morton and others (1980) and Bortugno (1987).

Although the Calico Fault did not clearly rupture within the study area during the Landers earthquake, minor discontinuous right-lateral surface fractures were reported in the Silver Bell Mine quadrangle just south of the Troy Lake quadrangle by Al Barrows and Steve Bezore of CDMG in July 1992 (field notes). One of these localities was 100 m (300 ft) south of the study area (Figure 2b) where 0.5 cm of right slip was measured. This location shows as weak vegetation tonal on the USDA (1952-53) air photos. Another 7 km (11 mi) to the southeast, a 400 m-long fracture zone with up to 2 cm of right slip was reported along previously mapped traces of the Calico Fault. Within the study area, a hairline crack was reported just west of the Calico Fault in Section 35 of the Newberrry Springs quadrangle (Figure 2a),

but this is undiagnostic and believed to be insignificant. As with the Newberry fractures, the minor ruptures on the Calico Fault are considered to be triggered slip.

A reinterpretation of the USDA (1952-1953) air photos by this writer is in close agreement with the recently active traces shown on the EFZ map (Figures 2a and 2b). However, there are differences in detail and some additional traces were based on relatively subtle features.

The principal evidence for Holocene recency are scarps, closed depressions, and tonal lineaments developed in late Quaternary deposits. Dibblee and Bassett (1966) map these deposits as Holocene and Pleistocene(?) alluvium, alluvial fan gravel and windblown sand. The sense of offset is provided by the southern bank of the modern Mojave River floodplain which appears to be right-laterally offset at least 400 m. A late Cenozoic right slip of about 10 km for the Calico Fault has been established by Dokka and Travis (1990a). This is a late Cenozoic slip rate of 1-1.7 mm/yr based on commencement of slip 6-10 mya. No Quaternary or Holocene slip rate has been determined for the Fault, although it connects to the southeast with the West Calico Fault which has an inferred right-lateral slip rate of 0.5-1 mm/yr based on the comparative development of fault-related geomorphic features (Hart and others 1988).

The Calico Fault has been trenched at only one locality in the study area. This was a consulting geologic investigation for a tract development located in Section 11, north of Valley Center Road in the Harvard Hill quadrangle (Figure 2a) (Academy Engineering, 1992; CDMG file #AP2637). Evidence of Holocene faulting was found in five trenches coincident with a linear northeast-facing scarp. The fault is shown as a single vertical strand on the somewhat generalized log, all alluvial units are offset to within 1 m of the surface, and only the uppermost "Qal B-horizon" (loose sand, yellow-brown, no ped development) is not faulted. The trenched faults do not quite align and are consistent with a left-step in the fault traces interpreted just north of the site (Figure 2a). According to the consultant (Academy Engineering, 1992 as reported by local property owners), the Calico Fault has created a groundwater barrier at the site, with water levels at a depth of 170-220 ft. southwest of the fault and 300-350 ft. northeast of the fault.

SEISMICITY

The seismic history of the Calico Fault and Newberry Fracture Zone is relatively short as the region was not adequately instrumented before 1969. Figure 4 shows that a number of earthquakes (maximum magnitude of 4.0-4.9) occurred close to these faults near the study area prior to 1985 (Caltech,

1985). The figure shows A and B quality or specially researched data only. None of these earthquakes are known to be associated with surface faulting. However, 2 or 3 inches of left-lateral surface rupture was reported on the Manix Fault after the 1947 M6.5 earthquake (Richter, 1958). In contrast, aftershocks of the Manix earthquake trend in a N30°W direction, which is consistent with a right-lateral first motion. Another earthquake of possible significance in the study area is the 1965 M5.2 earthquake (identified as Calico on Figure 4) that lies close to the Rodman or Calico Faults. Nur and others (1993) show this earthquake to have a right-lateral first motion with a N20°W trend. They speculate that a new fault system may be developing along the Landers-Manix trend which they call the Landers-Mojave earthquake line. The location and trend of the Newberry Fracture Zone is consistent with the trend and close to this new fault system. It also is within the Eastern California Shear Zone of Dokka and Travis (1990a and b). A possible correlation may exist with the Homestead Valley and Johnson Valley Faults, which displayed only minor rupture in 1979 but major rupture in 1992. Thus, the Newberry Fracture Zone may forewarn of a more significant rupture event and earthquake in the future.

Figure 5 is a map of aftershocks for a six-month period following the June 28, 1992 Landers earthquake, which shows a paucity of earthquakes near the Newberry Fracture Zone (Hauksson and others, 1993). Due to the lack of aftershocks, especially any in the M4 or 5 range, it is likely that the Newberry fractures were triggered by shaking. That is, shaking may have triggered a shallow strain event along the fracture zone.

Figures 5A and F identify a northwest-trending aftershock zone that corresponds with and extends the straight segment of the Calico Fault at the western margin of the study area. One earthquake in this zone was a M≥4.0. No surface rupture was reported in this area, although the ground may not have been checked carefully. The Calico Fault aftershock zone has a left-step relationship with the Barstow aftershock zone, which is consistent with the left-step or bend between the Calico and Blackwater Faults.

CONCLUSIONS AND DISCUSSION

The Newberry Fracture Zone (NFZ) is an active but very messy fault that appears to be a branch of the Calico Fault. At the surface, the NFZ consists of discontinuous multiple traces, which presumably are simplified and more continuous at depth. The south end of the fracture zone is a little more than 1 km from a distinct splay of the Calico Fault (Figures 2a and b). An intermediate faint tonal feature further suggests a possible link with the Calico Fault. Fractures that developed in 1992 during the June 28, 1992 Landers earthquake had a north to northeast

trend and formed a left-stepping pattern that extended over a distance of 10 km from north to south. Dominant displacements were normal, with as much as 11 or 12 cm of vertical offset and 5 cm of extension on individual fractures. The left-stepping pattern and observed northwest extension indicates the presence of an oblique right-lateral strike-slip fault or fault zone at depth.

Although the NFZ was not mapped prior to the 1992 earthquake, a review of pre-earthquake air photos reveals the existence of moderately well-defined left-stepping scarps and grabens that coincide with the 1992 ruptures in and north of Sections 22 and 23. The geomorphic features are developed on a surface of latest Pleistocene to Holocene age. The maximum vertical offset of the surface is about 2 m near Valley Center Road which, when compared to the maximum vertical offset of 11 cm measured in 1992, suggests perhaps 10 to 20 previous events during latest Quaternary time. Most of the Newberry fractures are very well-defined on the I.K. Curtis airphotos. The relationship with the Manix and Cady faults to the northeast of the NFZ is uncertain.

The southern set of NFZ fractures only locally coincide (i.e., in Section 26) with preexisting features in a rather diffuse zone of weak tonals (Figures 2a and b). However, a similar pattern of fractures and tonal lineaments in Section 35 suggests the possibility that some of the fracture-traces may have been located about 50m or so too far to the west. Because the fractures south of Section 26 are minor (less than 2 cm offset or extension) and presumably are mostly obliterated now, no effort was made to verify their location on the ground. Post-fracture air photos did not extend that far south.

The Calico Fault is part of a broad northwest-trending zone of faults referred to as the Eastern California Shear Zone (ECSZ) by Dokka and Travis (1990a, 1990b). They estimate a total right slip across the ECSZ of 65 km during the last 6-10 m.y. and a slip rate of 6-12 mm/yr. Geodetic measurements made by Sauber and others (1994) indicate a right-lateral strain rate across the south-central Mojave faults (Helendale Fault to Ludlow Fault) of about 12 mm/yr, which is consistent with the long term rate. If these figures are correct, then the ECSZ presently accommodates close to 25% of the motion between the Pacific and North American Plates.

The Calico Fault is a major element of the ECSZ, connecting with the West Calico and Hidalgo Faults to the southeast forming a major right-lateral fault zone about 90 km long. It also connects with the Blackwater Fault to the northwest via a left-step or bend (Figures 1 and 4). According to Dokka and Travis (1990a), a total of 10 km of right slip has occurred on the

Calico Fault during late Cenozoic time (last 6 to 10 ma). This equates to a slip rate of 1 to 1.7 mm/yr.

The Calico Fault can be mapped in the study area as a fairly well defined feature based on linear vegetation tonals, aligned dunes, low scarps and a few closed depressions developed on a latest Pleistocene to Holocene surface. The right-lateral offset (about 400 m) of the south margin of the Mojave River flood plain suggests offset in Quaternary time, but smaller offset drainages are generally lacking. Trenching in the study area also reveals evidence of Holocene offset, and the mismatch of strata indicates that strike-slip faulting is dominant. To the southeast of the area, the connecting West Calico Fault has -- based on comparative geomorphology with other faults having known slip rates -- an estimated late Quaternary right-lateral slip of about 0.5 to 1 mm/yr. Minor right-lateral surface faulting of 0.5 cm and 2 cm occurred in two places on the Calico Fault just south of the study area during the 1992 Landers earthquake.

The mapping of the Calico Fault by this writer is similar to photointerpretations made by Morton and others (1980) and Bortugno (1987) that were used to establish previous Earthquake Fault Zones (Figures 2a and 2b). However, this writer mapped the faults in a little more detail. In addition, the traces mapped on airphotos were carefully transferred to orthophoto maps before being traced onto the topographic base maps for this evaluation.

There is evidence that the Calico Fault is seismically active, based on the aftershocks following the Landers earthquake that coincide with the northwest end of the Calico Fault. The significance of earlier seismicity is less certain. However, the fracturing associated with the Landers earthquake and the aftershocks in the study area may forewarn of a future large earthquake and surface rupture event along the Calico and connecting faults in the next few decades, much as the minor ground ruptures on the Homestead Valley and Johnson Valley Faults apparently forewarned of the Landers earthquake.

RECOMMENDATIONS

Based on the preceding observations and conclusions, both the Newberry Fracture Zone and the Calico Fault are Holocene active and are well-defined as surface features. These faults clearly meet the zoning criteria established under the Alquist-Priolo Earthquake Fault Zoning Act (Hart, 1994). Therefore, it is recommended that new and revised zoning be established as follows:

Newberry Fracture Zone:

1. Zone all of the 1992 fractures as shown on Figure 3 in the Harvard Hill, Newberry Springs and Troy Lake quadrangles. Also, zone the better-defined scarps and tonal lineaments that provide continuity with the 1992 fractures (highlighted in yellow on Figure 2a).

2. Do not zone the hairline cracks in Sections 34 and 35, which are very minor and do not align with known faults. Also, do not zone the traces of Barrows and Bezore, with one exception (highlighted in yellow), as their traces were reconnaissance and have been largely relocated.

3. The principal references to be cited in each of the quadrangles are Unruh and others (1994), Lajoie (1994) and this FER.

Calico Fault

1. Revise the existing zones using the principal traces as highlighted in yellow on Figures 2a and b.

2. Do not zone the minor, subtle tonal features unless they are projections of better defined traces.

3. The principal reference to be cited is this FER. However, Morton and others (1980) should be cited as a supporting reference on each of the proposed zone maps.

Report Prepared by:

Earl W. Hart

Earl W. Hart
Senior Geologist
CEG 935
August 26, 1994

Reviewed by

Jerry Treiman
CEG 1035
9/8/94

REFERENCES CITED

Academy Engineering, 1992, Engineering geology report, Tentative Tract 15388, APN 515-171-014, Daggett area, San Bernardino County, California: Unpublished consultants report of January 22, 1992 with supplement of May 7, 1992 (CDMG file #AP2637).

Bortugno, E.J., 1987, Calico, West Calico, Hidalgo, and related faults, San Bernardino County, California: California Division of Mines and Geology Fault Evaluation Report FER-184 (unpublished), 9 p., maps, scale 1:62,500 and 1:24,000.

Bortugno, E.J., and Spittler, T.E., 1986, Geologic map of the San Bernardino quadrangle, California: California Division of Mines and Geology Regional Geologic Map Series, Map No. 3A, 5 sheets (Recency of faulting, Sheet 5), scale 1:250,000.

Bull, W.B., 1978, Tectonic geomorphology of the Mojave Desert, California: U.S. Geological Survey Technical Report 14-08-0001-G-394, 188 p. (unpublished).

California Division of Mines and Geology, 1988, Official Maps of Earthquake Fault (Special Studies) Zones, Harvard Hill, Newberry Springs and Troy Lake quadrangles, 1:24,000 scale.

California Institute of Technology, 1985, CALNET earthquake data (preliminary).

Dibblee, T.W., Jr., and Bassett, A.M., 1966, Geologic Map of the Newberry quadrangle, San Bernardino, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-461, scale 1:62,500.

Dokka, R.K., and Travis, C.J., 1990a, Late Cenozoic strike-slip faulting in the Mojave Desert, California: Tectonics, v. 9, p. 311-340.

Dokka, R.K., and Travis, C.J., 1990b, role of the Eastern California Shear Zone in accommodating Pacific-North American Plate motion: Geophysical Research Letters, v. 17, p. 1323-1326.

Hart, E.W., 1994, Fault-rupture hazard zones in California: California Division of Mines and Geology Special Publication 42 (revised), 34 p.

Hart, E.W., Bryant, W.A., and Treiman, J.A., 1993, Surface faulting associated with the June 1992 Landers earthquake: California Geology, v. 46, p. 10-16.

Hart, E.W., Bryant, W.A., Kahle, J.E., Manson, M.W., and Bortugno, E.J., 1988, Summary Report: Fault Evaluation Program, 1986-1987, Mojave Desert and other areas: California Division of Mines and Geology Open-File Report 88-1, 40 p.

Hauksson, E., Jones, L.M., Hutton, K., and Eberhart-Phillips, D., 1993, The 1992 Landers earthquake sequence: Seismological observations: Journal of Geophysical Research, v. 98, n. B11, p. 19,835-19,858.

I.K. Curtis, 1992, Aerial photographs of Newberry Springs, black and white, vertical, low sun (morning), scale 1:4,000, flown 8/24/92, Flights 1 to 7.

Jennings, C.W., 1992, Preliminary fault activity map of California: California Division of Mines and Geology Open-File Report 92-03.

Lajoie, K.R., 1994, Unpublished mapping of surface fault rupture associated with the 28 June 1992 Landers earthquake: U.S. Geological Survey, 1:4,000 scale.

Lettis, W.R., and Kelson, K.I., 1992, Patterns of surficial deformation in the Newberry Springs area and the Johnson Valley-Homestead Valley stepover associated with the 1992 Landers earthquake: EOS (Transactions, American Geophysical Union), Fall Meeting Abstract Supplement, v. 73, no. 43, p. 363.

Morton, D.M., Miller, F.K., and Smith, C.C., 1980, Photoreconnaissance maps showing young-looking fault features in the southern Mojave Desert, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1051, 7 sheets, scales 1:24,000 and 1:62,500.

Nur, A., Ron, H., and Beroza, G., 1993, Landers-Mojave earthquake line: A new fault system?: GSA Today, v. 3, no. 10, p. 253, 256-258.

Richter, C.F., 1958, Elementary seismology: W.H. Freeman and Company, San Francisco, CA, 768 p.

Sauber, J., Thatcher, W., Soloman, S.C., and Lisowski, M., 1994, Geodetic slip rate for the eastern California shear zone and the recurrence time of Mojave desert earthquakes: Nature, v. 367, p. 264-266.

Sieh, K., Jones, L., Hawksson, E., Hudnut, K., Eberhart-Phillips, D., Heaton, T., Hough, S., Hutton, K., Kanamori, H., Lilje, A., Lindvall, S., McGill, S., Mori, J., Rubin, C., Spotila, J.A., Stock, J., Thio, H.K., Treiman, J., Wernicke, B., and Zachariasen, J., 1993, Near-field investigations of the Landers earthquake sequence, April to July 1992: Science, v. 260, p. 171-176.

Toppozada, T.R., and Wilson, R.I., 1992, April 22 Joshua Tree, and June 28 Landers and Big Bear earthquakes, 1992: California Geology, v. 45, no. 4, p. 118-120.

U.S. Department of Agriculture, 1952-1953, Aerial photographs, black and white, vertical, scale 1:20,000, AXL-14K-170 to 178, 44K-2 to 9, 14K-168 to 169, 51K-4 to 8, 16K-66 to 71, 39K-35 to 38, 16K-201 to 202, 17K-141 to 144.

Unruh, J.R., Lettis, W.R., and Sowers, J.M., 1994, Kinematic interpretation of the 1992 Landers earthquake: Bulletin of the Seismological Society of America, v. 84, no. 3, p. 537-546, Figure 5 scale 1:48,000.

William Lettis & Associates, Jan. 1993 (draft), Landers earthquake investigation: Unpublished report for Pacific Gas and Electric company; includes map of Newberry Fracture Zone, 1:24,000 scale, modified 1993 by J.M. Sowers.

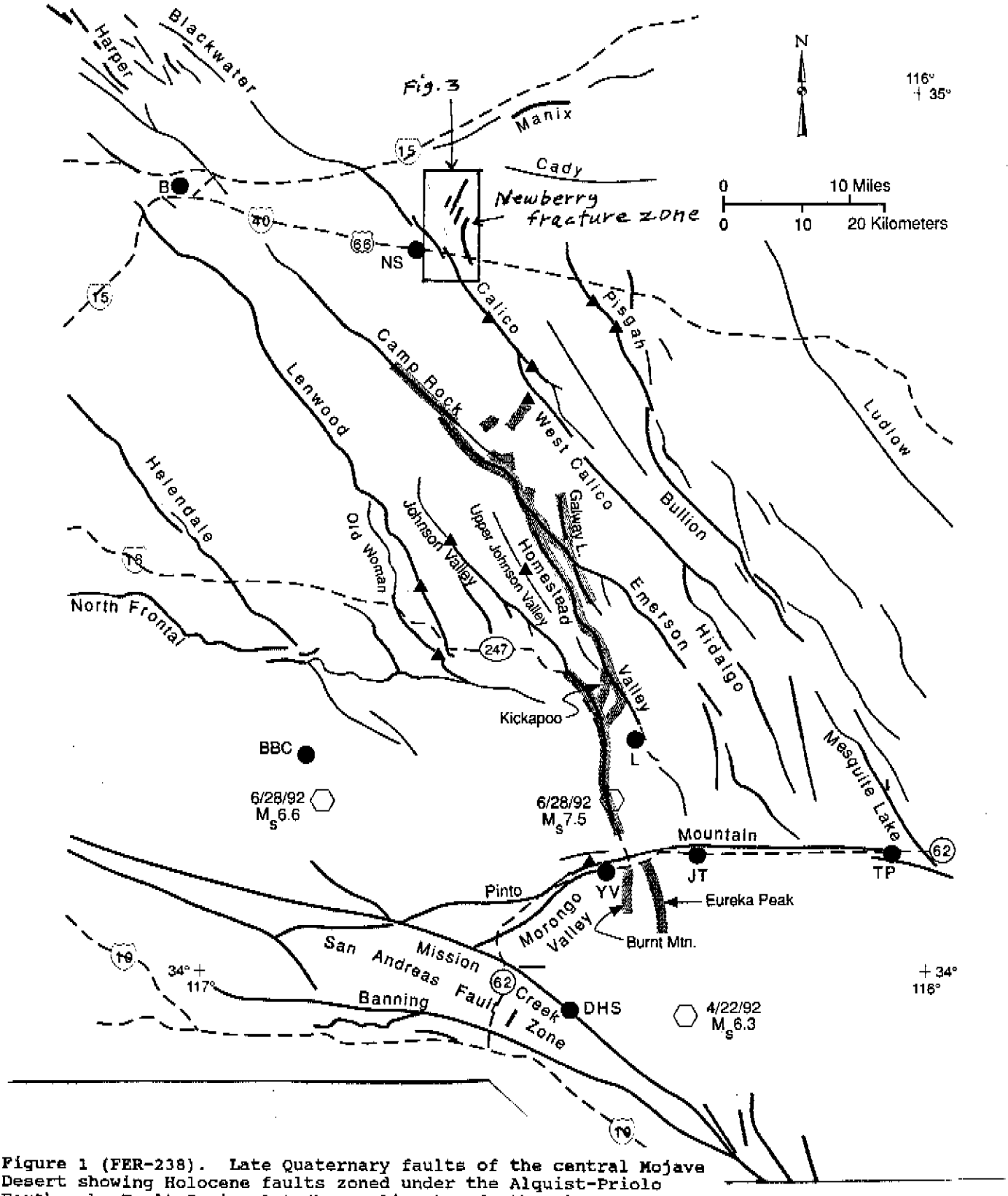


Figure 1 (FER-238). Late Quaternary faults of the central Mojave Desert showing Holocene faults zoned under the Alquist-Priolo Earthquake Fault Zoning Act (heavy lines) and other late Quaternary faults (light lines). Surface rupture zones associated with the Landers earthquake are identified by wide gray (shaded) lines; triggered slip on the Newberry fracture zone is shown in red and slip localities on other faults are shown by triangles. Hexagons mark epicenters. Letters identify cities: B=Barstow; BBC=Big Bear City; DHS=Desert Hot Springs; JT=Joshua Tree; L=Landers; NS=Newberry Springs; TP=Twentynine Palms; YV=Yucca Valley (Modified from Hart and others, 1993).

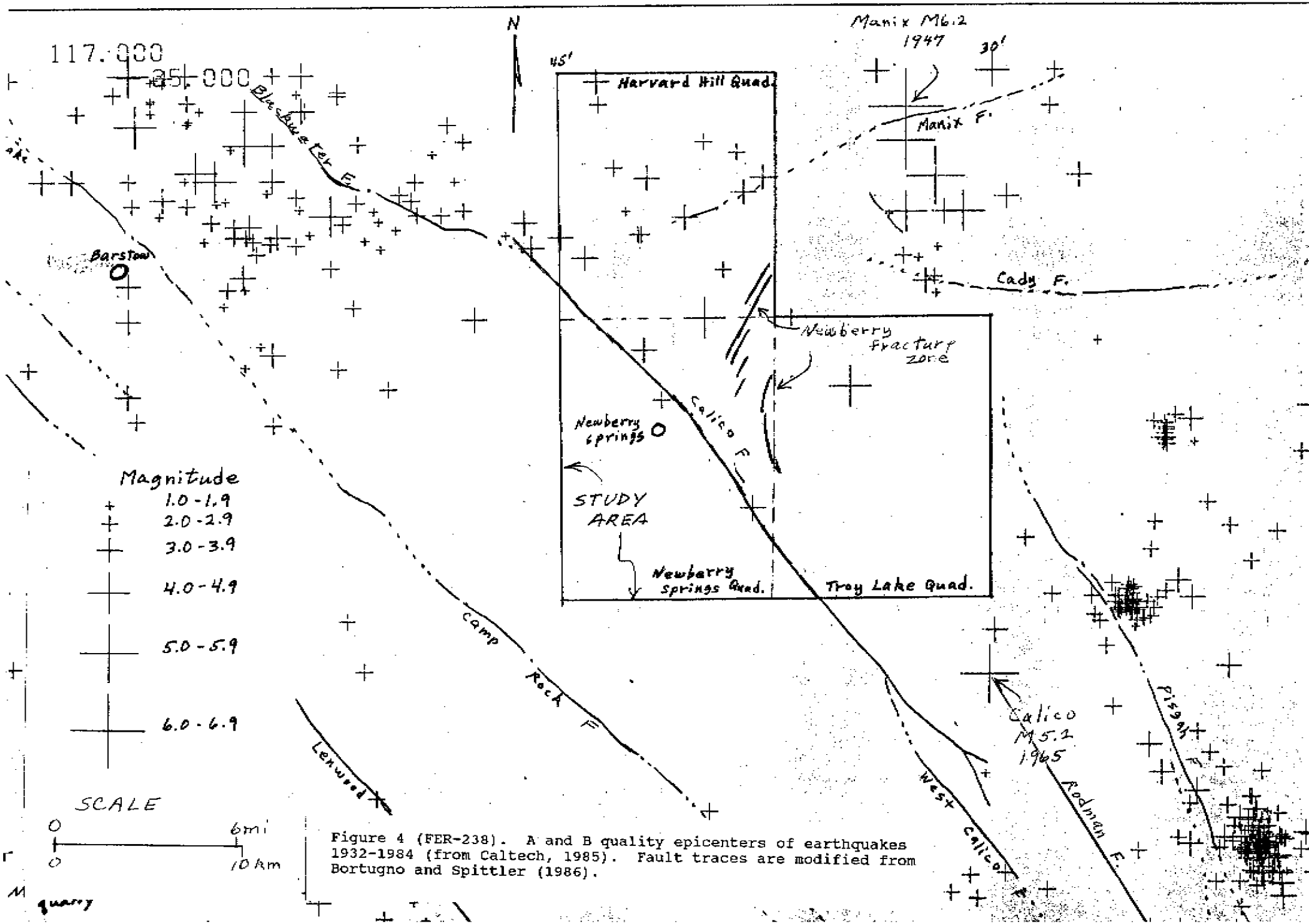


Figure 4 (FER-238). A and B quality epicenters of earthquakes 1932-1984 (from Caltech, 1985). Fault traces are modified from Bortugno and Spittler (1986).

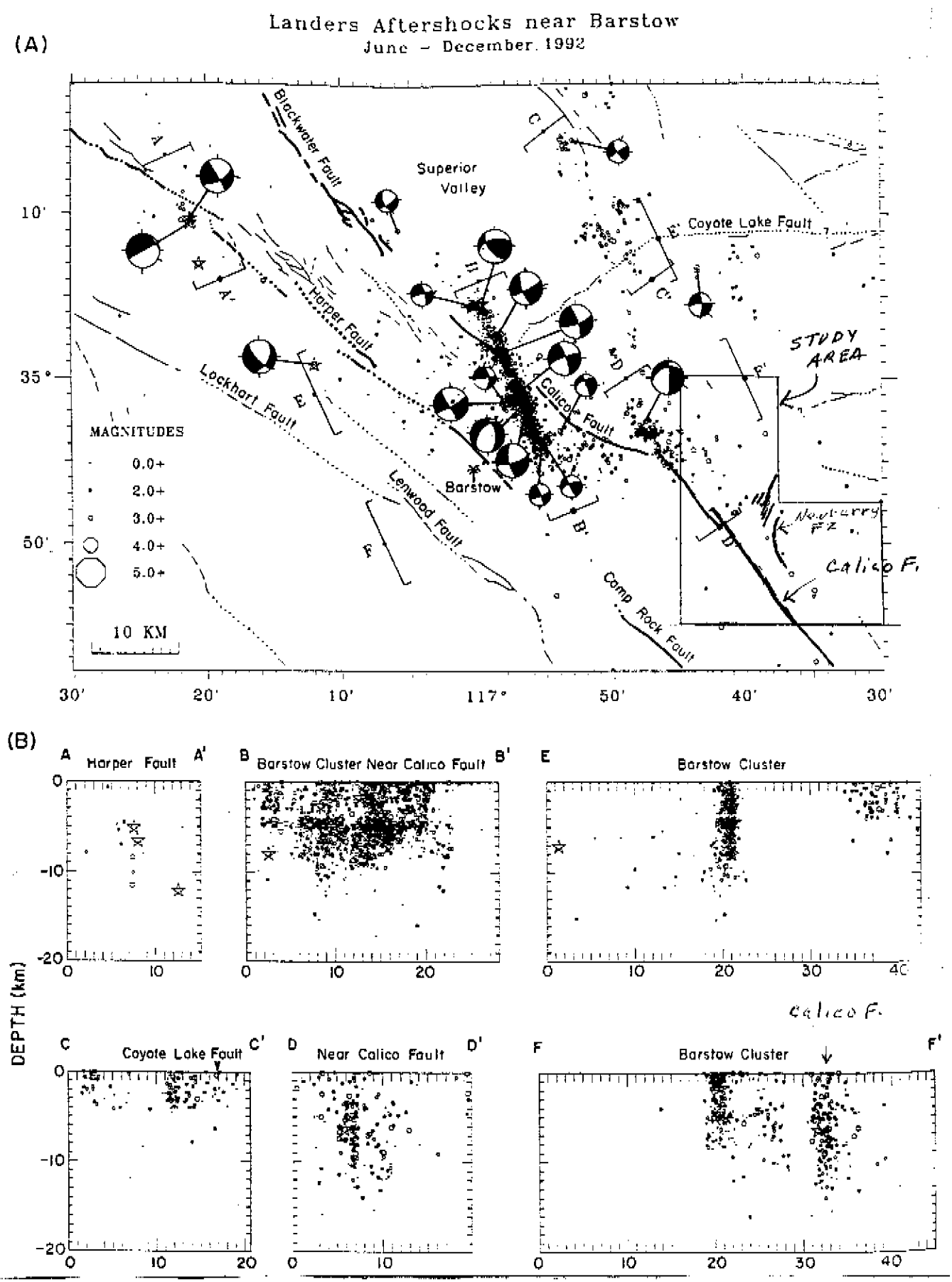


Figure 5 (FER-238). **Aftershocks of the Landers earthquake near** Barstow. a) Map showing major faults and location of aftershocks from June 28 to December 31, 1992. Lower-hemisphere, first-motion, focal mechanisms of typical events are also shown. b) Cross sections showing the depth distribution of aftershocks. Earthquakes of ≥M4.0 are shown by stars. (After Hawksson and others, 1993, Figure 12.)

APPENDIX A To FER-238

Photo-Interpretations and Field-checked Ruptures of the Newberry Fracture Zone by K.R. Lajoie

The attached strip maps are mosaics of air photo overlays interpreted by Kenneth R. Lajoie of the U.S. Geological Survey, Menlo Park, January 1994. The strip maps show observed and interpreted fault ruptures using normally exposed photos plus some specially darkened and/or lacquered photos. The map symbols are identified on the Explanation (Sheet 1 of 9). Data on the flight and photo numbers, quadrangle (initials) and date (month/year of interpretation) appear at the bottom of each strip (Sheets 2 to 9). Ruptures checked in the field in October 1993 by Lajoie are identified by red annotations (see Explanation).

Faults verified by this writer (Hart) are identified by a check-mark, but not all of the rupture traces could be verified using "normal" air photos. It is believed that the interpretations of Lajoie are the most complete of any data set and that the traces are accurately located. Moreover, the data on these mosaics can be very useful in planning geologic investigations and locating structures so as to avoid or minimize possible future rupture.

These mosaics should be used with the 1:4000-scale, black and white I.K. curtis air photos of the Newberry Springs area flown 8/24/92 (5 flight lines). Copies of photos can be obtained from I.K. Curtis Services, Inc., 2919 Empire Avenue, Burbank, CA 91504 (ph. 818-842-5127). A set of these photos also is on file at the San Francisco Office of CDMG (currently 185 Berry Street, Suite 3600, San Francisco, 94107; phone 415-904-7707).

MAP SYMBOLS

for

LAJOIE'S PHOTO-INTERPRETIVE MAPS OF THE NEWBERRY SPRINGS AREA

All information in black mapped from photos:


Building


Road


Pond


Fence


1992 Ground rupture

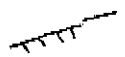
All information in red pencil from field work by Lajoie 11/93:

LS Left-stepping en-echelon rupture

EX Extensional rupture


Up/Down, relative vertical rupture displacement


Rupture verified


Rupture scarp, hachures on downthrown side


Rupture (crack) mapped only in field

NC No crack (no rupture)


Rupture mapped on photo, but no evidence in field

Photo verification by E.W. Hart

✓ Rupture trace verified

? Rupture questionable